Reply to "Comment on 'Perturbative operator approach to high-precision light-pulse atom interferometry'"

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Recently, we introduced [C. Ufrecht and E. Giese, Phys. Rev. A **101**, 053615 (2020)] a technique to calculate the phase of light-pulse atom interferometers caused by the presence of perturbation potentials and underlined its power by an illustrative example. In the preceding Comment [B. Dubetsky, Phys. Rev. A **102**, 027301 (2020)], it was pointed out that other, less idealized situations could have been calculated as well. Our Reply emphasizes that our method is correct, the results from our example can be trivially generalized to other perturbations, and intricate effects of local environments can be even more prominent but also treated by our technique.

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In Ref. [1], we introduced an operator-based method to calculate the phase of a light-pulse atom interferometer caused by perturbing potentials. To illustrate the technique, we calculated the phase originating from the cubic contributions in the Taylor expansion of the gravitational potential of a spherical Earth, which we referred to as second gravity gradients.

The Comment [2] does not criticize our method, but merely points out that using the geoid rather than our idealized example may lead to different coefficients of the Taylor expansion and consequently to different phases in the signal. We are of course well aware of the necessity to carefully assess and locally analyze Earth's gravity [3] for high-precision measurements [4]. However, we welcome this opportunity to elaborate on the significance of local potentials and the applicability of our method, which is particularly suited for such situations.

We emphasize that (i) our technique is valid for arbitrary perturbing potentials under the conditions detailed in Ref. [1] and therefore of course also applies to the values of the second gradient's components roughly estimated in the Comment; and (ii) local gravitational fields may vary on short length scales and therefore must not be described by Taylor expansion over the interferometer extent, even though they can be treated by our method as well by the direct application of Eq. (2) from our article.

Indeed, there are multiple effects that can mask second gravity gradients of a spherical Earth, among them the example discussed in the Comment. However, local gravitational effects from buildings, or the terrain and landscape can even be more prominent. In addition to these contributions, one needs to take into account further gravitational fields that arise from hydrogeological effects, tidal range, etc. [5,6]. Because such effects have to be evaluated locally for each individual setup, we focused in our example on the illustrative case of an idealized Earth instead of discussing the details of experiment-specific contributions. In this spirit, we stress the general applicability of our example to universal cubic perturbing potentials.

While the expansion performed in our example can be trivially adopted to the case mentioned in the Comment by simply replacing the expansion coefficients, we emphasize that local gravitational perturbations may vary on length scales considerably smaller than the region probed by the interferometer experiment [7]. Such contributions must not be described by the Taylor expansion assumed in the Comment and consequently one has to resort to Eq. (2) of our article. Our method can therefore be applied to much more relevant and general perturbations than those pointed out in the Comment.

Similarly, other local potentials of nongravitational origin such as magnetic fields [8] or blackbody radiation [9] can also lead to major phase contributions, as already mentioned in the abstract of Ref. [1], and their effects can be evaluated through our technique as well.

[1] C. Ufrecht and E. Giese, Perturbative operator approach to high-precision light-pulse atom interferometry, Phys. Rev. A **101**, 053615 (2020).

[2] B. Dubetsky, Comment on "Perturbative operator approach to high-precision light-pulse atom interferometry," preceding Comment, Phys. Rev. A **102**, 027301 (2020).

[3] J. C. Ries, R. Eanes, Z. Kang, U. Ko, C. McCullough, P. Nagel, S. Bettadpur, N. Pie, S. Poole, T. Richter, H. Save, and B. D. Tapley, The development and evaluation of the global gravity model GGM05, The University of Texas at Austin, Center for Space Research Report No. CSR-16-02, 2016.

[4] G. D'Agostino, S. Merlet, A. Landragin, and F. Pereira Dos Santos, Perturbations of the local gravity field due to mass distribution on precise measuring instruments: A numerical method applied to a cold atom gravimeter, Metrologia **48**, 299 (2011).

[5] B. Canuel, S. Abend, P. Amaro-Seoane, F. Badaracco, Q. Beaufils *et al.*, ELGAR—A European laboratory for gravitation and atom-interferometric research, arXiv:1911.03701.

[6] J. Junca, A. Bertoldi, D. O. Sabulsky, G. Lefèvre, X. Zou, J.-B. Decitre, R. Geiger, A. Landragin, S. Gaffet, P. Bouyer, and B. Canuel, Characterizing Earth gravity field fluctuations with the MIGA antenna for future gravitational wave detectors, Phys. Rev. D **99**, 104026 (2019).

[7] M. Schilling, É. Wodey, L. Timmen, D. Tell, K. H. Zipfel, D. Schlippert, C. Schubert, E. M. Rasel, and J. Müller, Vertical gravity profile in a 10 m atom interferometer, arXiv:2003.04875.

[8] É. Wodey, D. Tell, E. M. Rasel, D. Schlippert, R. Baur, U. Kissling, B. Kölliker, M. Lorenz, M. Marrer, U. Schläpfer *et al.*, A scalable high-performance magnetic shield for very long baseline atom interferometry, Rev. Sci. Instrum. **91**, 035117 (2020).

[9] P. Haslinger, M. Jaffe, V. Xu, O. Schwartz, M. Sonnleitner, M. Ritsch-Marte, H. Ritsch, and H. Müller, Attractive force on atoms due to blackbody radiation, Nat. Phys. **14**, 257 (2018).